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Methodology for the Analysis of Coal Quality: A Systematic Literature Review

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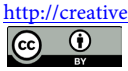

Abstract

Mineral coal presents a historical chronology to society, mainly regarding energy generation, and is outstanding in relation to oil when the subject is electricity generation, besides being utilized in the cosmetics and coal gas industry. Thus, the production chain that uses mineral coal must be validated for quality, considering specific prerequisites that show the positivity of this analysis. For this purpose, the present study was characterized by a Systematic Literature Review (SLR), aiming to identify scientific productions that listed the topic of mineral coal quality considering the Science Direct database. In this way, based on the combination of the term "coal quality", the search found 1794 results, covering the period from 2010 to 2022. The articles that dealt specifically with methods to analyze the quality of mineral coal were classified in order to develop the study. Furthermore, it was found that few publications really discuss the qualification of the coal as their central topic, since the manuscripts showed measurement methods connected to algorithms and the use of mathematical calculations. A gap was also observed in the studies, because they did not consider the coal production chain and the necessary management between the parts of the process, evidencing as a proposition for future work a methodology applied to a computational model that covers the management of coal quality.

Subject Areas

Materials Engineering, Mineral Engineering

Keywords

Coal Quality, Mineral Coal, Quality Control, Qualification Method

1. Introduction

In the last few centuries, humankind has sought to increase its capacity for power production in order to develop industry, means of transport, and quality of life. Since the recent energy crisis, researchers and industries have attempted to manage energy more competently by increasing power system efficiency [1].

In Brazil, about 70% of the electricity is generated by hydropower plants, but the national electricity generation system has undergone significant changes in normative resolutions n˚ 500/2012 and n˚ 579/2013 of the National Agency of Electric Energy (ANEEL—Agência Nacional de Energia Elétrica). Thermoelectric power generation, based on fossil or non-fossil fuels, including nuclear energy, is an inevitable part of this scenario [2].

The most important Brazilian coal deposits occur in the south of the country, with marked coal development in the states of Rio Grande do Sul and Santa Catarina. The proven coal reserves are on the order of 32 × 109 tons, 89.2% of which are located in the Rio Grande do Sul, 10.4% in Santa Catarina, and the remaining 0.4% in the states of Paraná and São Paulo [3].

In the south of the state of Santa Catarina, the Jorge Lacerda Thermoelectric Complex with an installed capacity of 857 MW is one of the most important power generation plants in the country since the 1960s. The complex was founded in 1957 for two purposes: to make use of part of the mineral coal (steam coal) extracted from the mines in the region and to generate energy at a time in which the rate of industrial development is growing fast. The first unit, called Jorge Lacerda I, with a 50 MW capacity, was inaugurated by President Marshal Castello Branco on July 3, 1965. The second unit, Jorge Lacerda II, came online in March 1966, with the same capacity. This complex consisted of seven generator sets, grouped into three plants: Jorge Lacerda A, with two 50 MW generator units and two of 66 MW each, Jorge Lacerda B, with two 131 MW units each, and Jorge Lacerda C, with one generator unit of 363 MW, a total of 857 MW. The physical guarantee for commercializing its energy is 649.9 MW on average and its authorization to operate is valid until 2040, as approved by PL 712/2019, approved by the Federal Senate on December 16, 2021 [4].

ANEEL, an agency that operates under a special regime to regulate the public service of electric energy, was established by Law n˚ 9427, of December 26, 1996, constituted by Decree n˚ 2335, of October 6, 1997. It was the first entity of this nature created in Brazil and connected to the Ministry of Mines and Energy. The special agency was established to regulate a highly complex sector, relevant both from the social and economic standpoint, with competences defined by law, involving from the regulation proper to the inspection of regulated agents, directly reaching electric energy generating companies, distributors, and users [5].

Through Normative Resolution n˚ 500, of July 17, 2012 (REN2012500), the General Director of ANEEL determined that the cost of consuming fuels for the thermoelectric generation of a company located within the National Interconnected System (SIN-Sistema Interligado Nacional), which were to use only na-

tional mineral coal might be reimbursed up to the limit of 100% of the corresponding expenditure, with resources from the Energy Development Account (CDE—Conta de Desenvolvimento de Energia). The percentage of this reimbursement is measured according to the generation efficiency of each generator park, and the company responsible for generation must bear its costs if the efficiency goals established in ANEEL Resolution 500/2012 are not met.

This commitment of the generator to efficiency goals for their generator parks aimed at "forcing" the thermal parks to modernize. However, since the reimbursement of fuel via CDE will only occurs until 2040, there would not be enough time to amortize the investments needed for this modernization. What in fact occurred was the decommissioning of old thermal parks such as Charqueadas/RS and phase A of Candiota/RS. Another aspect resulting from this resolution was the change in the system of fuel purchase by the generator.

As a complement, until December 2015, the then Tractebel Energia (Santa Catarina), now Engie Brasil, celebrated a single contract to supply CE4500 coal with a consortium of supplying companies, paying the same price to all of them. Beginning in January 2016, the contracts celebrated were individualized per coal supplying company, and a different price was paid to each of them, according to a technical and economic evaluation performed previously by Engie Brasil.

For billing purposes, every month Engie Brasil checks the amounts and quality of the coal supplied. In the previous contract, the amount counted was that which the consortium of companies had supplied, but in the current contract, the amounts are counted individually, by company. Nevertheless, quality continued to be counted jointly, because it would be unfair to fine the coal supply which, although it individually generates deviations, jointly fulfills the contractual specifications of supply. However, the fine imposed, which in the previous contract was paid for by an extra supply of coal, became financial, in the form of an annotation on the billing.

The economic and financial impact of the fines became very large, requiring the companies to exert strict control of the quality of the supply, thus, since the quality is checked jointly, the lots had to be released in a centralized manner, which shows the great importance, not only of the technical aspect of the quality of the coal to be utilized, but also of the management of the process which surrounds it.

Therefore, the aim of the present study was to perform a Systematic Literature Review (SLR), evidencing studies that permeate the universe of coal quality analysis, considering the knowledge about what the state of the art reveals on this topic.

2. Theoretical Reference

During the Industrial Revolution, technology in the sense known in modern times began to present more constant and significant progress. After the steam

engine was created by James Watt in 1769, the techniques that depended on energy evolved and provided immediate benefits to the textile industry and transport sector, with the rise of the railways. Next, especially important was the invention of generators and electric motors, applied immediately to heat generation and lighting. Further research on motors led to discover the internal combustion engine which inaugurated the era of oil-derived fuels. At this point, the prototype of the automobile appeared. The energy use techniques that favored exploring new resources, had great repercussions, not only on industry, but also on society in the 19th century [6].

Mineral coal also had a marked participation in the Industrial Revolution in the beginning of the 18th century in England. It was driven by the development of technology to manufacture steel, a process in which coal plays an active role. Consequently, the main nations that had reserves began to develop steel equipment and tools that ultimately replaced animal force and water power by mechanical force. During this period, countries that had natural reserves of iron ore and coal experienced an economic growth unprecedented in their history [7].

Historically, 400 million years ago, many natural factors began the physical-chemical process whose product would be mineral coal. In South America several mineral coal basins were found, one of them with reserves estimated at 3.2 billion tons, situated in the South region of the state of Santa Catarina, distributed over an area 100 kilometers long and 20 kilometers wide [8].

In a simple definition, mineral coal is a non-renewable sedimentary rock, which originated thousands of years ago and is found in the subsoil in deposits of organic origin. Chaves [9] also adds a complementation, mentioning that it is a heterogeneous material in terms of petrographic and structural constitution, which has a great amount of pores, cracks, interfaces and capilarities, to such an extent that it can be considered a pre-fractured solid. It has moisture that is not always visible to the naked eye, since it is contained inside the coal particles and not on their surface, as seen in other minerals.

As regards the chemical aspect, coals are differentiated by the high carbon content, generally between 55% and 95%. According to this content, types range from the least rich to the richest in carbon: peat, lignite, bituminous coal and anthracite. These varieties of coal constitute the series of coals and indicate the degree of evolution in the course of transforming vegetable matter, *i.e.* the degree of carbonification. Besides this evolutionary classification, it is also important to highlight the grade, which is the relation between organic matter and inorganic matter in the layer. Thus, peat may contain from 55% to 60% carbon; lignite, from 67% to 78%; bituminous coal, from 80% to 90%; and anthracite, 96%. As to coal age, most of it was formed during the Cretaceous period, and mainly in the Tertiary. More than half (54.78%) of the known reserves are from this phase. The coal from the carboniferous age totalizes 23.74% of the world reserves, and those of the Permian age, 16.91%. Brazilian coal is from the Permian age [10].

The world has extensive reserves of mineral coal: 847.5 billion tons, an amount

sufficient to meet annual production for 130 years. Seventy-five countries have significant reserves, the United States, Russia and China having 60% of the total volume. The classification of the greatest coal producers in 2010 showed China, United States, the European Union, Australia, Russia and Indonesia. China is responsible for almost half the world production (3240 million tons in 2010) and has reserves for 35 years [10]. Also, the largest exporters are: Australia, Russia, United States, Indonesia and Canada [11].

Coal India, the largest world producer, expects consumption to be driven forward as the steel, cement and aluminum industries return to their pre-COVID-19 Pandemic levels of production. The company approved more than US $6 billions for investments in new mines and expansions, and thus, the USA plants intend to consume 16% more compared to 2020, and project a new increase of more than 3% in 1922, as declared by the country's Administration of Information about Energy. China and India, which together are responsible for almost two-third of the global demand, do not have plans to cut down in the short term [12].

In the light of the context presented, it is perceived that coal has been part of man's life for a very long time. Although it was ignored by the indigenous peoples, it soon aroused the curiosity of the Imperial Government, giving rise to many research studies. As a result, the exploration and commercialization of mineral coal were essential to the growth and socioeconomic development of the south region of the state of Santa Catarina, throughout the 20th century, generating jobs and leveraging other productive activities [8].

In Brazil, mineral coal supplies the economy, especially the thermoelectric plants that consume about 85% of the production. On the other hand the cement industry in the country is supplied with approximately 6% of this coal. Thus 4% is left for paper pulp (cellulose) production and only 5% for the food, ceramics and grain industries. Worldwide, coal is also utilized to produce cosmetics, coal gas, and, among many other products are the by-products of coal that constitute synthetic materials [13].

Returning to Santa Catarina, in 1922, when it was concluded that the quality of the coal found by drovers in the Rio do Rastro Mountain Range was good, this fact was decisive to attract investments in the mining activity in this region. It led to studies to characterize the ore and its economic feasibility based on samples sent to Europe. Then, in the beginning of the 20th century, aiming to speed up the coal industry, the Brazilian Government created the Committee of Studies on Hard Coal in Brazil (Comissão de Estudos das Minas de Carvão de Pedra no Brasil) [14].

Furthermore, the great automation of processes in computational enviroments has made a difference for many organizations. These automations have aroused the enthusiasm of various sectors, including that of coal processing, which in Santa Catarina is operated by the Union of the Coal Extraction Industry of the State of Santa Catarina (SIECESC—Sindicato da Indústria de Extração de Carvão do Estado de Santa Catarina). This process is controlled practically in an artisan-

al form, with a few measurements on loose and decentralized spreadsheets.

Nevertheless, the policy to provide incentives to coal slowed down and, when the economic miracle ended in the 1980s, the State began to intervene less and less, and in 1990 reached the point of no longer obliging the steel foundries to purchase Brazilian metallurgical coal. Thus, in the course of mining activities, this sector has been observing periods of great economic development alternating with periods of intense crisis, evidencing the lack of a public policy capable of ensuring a productive and institutionally balanced environment [14].

3. Methodology

When a new topic is analyzed, a few contradictory results may be found. One of the alternatives to solve this type of problem is to base them on scientific productions of quality concerning the topic studied. This led to a new research design: the Systematic Literature Review (SLR).

SLR is defined as a research model that follows specific methods and seeks to give some congruence to a large collection of documents [15]. According to Cordeiro *et al.* [16], the SLR also allows the researcher to gather, critically assess and conduct a synthesis of the results of multiple primary studies.

In order to analyze the research data, the authors selected the Science Direct scientific database, considering the most promising search terms regarding the universe of coal, its quality and related aspects.

For this purpose, **Table 1** shows the result of the search performed based on the combination of the terms considering the time period from 2010 to 2022.

Table 1. Search terms and results according to each year.

Year	Coal Quality	Coal Management	Coal Manager	Coal Administration
2010	58			1
2011	85			2
2012	98	2		1
2013	115	1	3	
2014	129	1		
2015	118	2		1
2016	147	3		
2017	155	4		
2018	162	6		
2019	181	2		1
2020	195	2		
2021	207	8	1	
2022	144	5	1	
TOTAL	**1794**	**36**	**5**	**6**

Note: Elaborated by Authors (2022).

Indeed, reading Table 1 clearly shows that most studies are connected to the topic of coal quality, for which 1794 results were obtained. However, it is highlighted that the characterization was of a wide search that grouped studies in which some point of the manuscript was considered in "coal quality" terms.

As regards the article qualification filters, only those whose central topic was the quality of mineral coal were considered, and the main journals identified with publications about this were: Fuel (219 articles), International Journal of Coal Geology (168 articles), Energy (88 articles), Journal of Cleaner Production (59 articles), Fuel Processing Technology (48 articles), Applied Thermal Engineering (45 articles), besides others with the publication of less than 40 articles in the last almost twelve years.

Furthermore, on utilizing the advanced search engine in the Science Direct base to identify the coal quality terms covered only in the title, abstract and key-words, considering the same time variable described previously, only 191 publications were found, denoting that coal quality as a central topic has not yet been much discussed and has space for further research in this field, both as regards methodologies to evaluate the property of coal and aligned to management.

4. Results and Discussions

A few studies are outstanding among the findings in the literature regarding coal quality. In the first it was found that Random Forest (RF) may be a new and sensitive data mining tool for measures of variable importance by means of many properties of coal for the prediction of coke quality. According to the results found, supplying the closeness of non-linear interdependence among parameters for variable choice, the non-parametric predictive model may be developed as a reliable, accurate action to get to know the complex relationship by means of research on fuel and energy [17].

In the later study, it was shown that the coal gasifier, an important part of the combined cycle of integrated gasification, transforms coal into synthesis gas (syngas) after reaching a given pressure and temperature. The characteristics of synthesis gas are very much guided by the characteristics of coal and thus interfere in energy generation. As conclusions, the authors said that the results of the tests identified the fact that the correct PI controller clearly meets the restrictions in all load requirements and supplies better answers for the changes in coal quality [18].

Mishra *et al.* [19] present another article that should also receive attention. It refers to the behavior of various types of coal, showing that this attitude depends on the properties of its ash. These are the most relevant characteristics in the design and operation of commercial boilers. Also, the authors of the work mentioned that the linear return analysis of the high temperature ash composition shows a path that can be utilized to indicate the predictive indices of slagging, incrustation and propensity to abrasion during the period of the combustion ac-

tions.

Begum *et al.* [20] begin their study emphasizing that coal plays a relevant role in meeting the global need for energy. Thus, they point out that it is necessary to classify the different categories of coal to organize the mining and mixing operations. For the purpose of creating a model of a system that could supply this need, having as principle the spectral properties of reflectance, the authors point out that the choice of the model of a machine is the determinant factor to obtain the desired accuracy of classification systems. Therefore, in their study classifiers were used related to different paradigms: Logistic Regression, Random Forest (RF) and Support Vector Machine (SVM).

As regards automation and the universe of coal quality, Zhang *et al.* [21] proposed algorithms FEED and PERS for the online image of coal, based on the detection of multi-information concerning the qualification, where the mean errors of this detection were less than 3.5%. The authors also pointed out the importance of automation in the development of coal engineering, validating the significance of the study based on the view of an information machine about the qualifications of coal in terms of distribution of the size and density, ash content of each density and total ash content.

Likewise, previously the study by Zhou and O'Brien [22] also surveyed the use of an algorithm, but based on the neural network methods, Radial Basis Function (RBF), developed to measure the quality parameters of coal by means of the geophysical aspects that are routinely obtained, such as density, gamma and sonic rays. This approach based on RBF was determined utilizing a compound of self-controlled training data and another of independent data from two mines. The finding of this study was that the accuracy of measurement of the coal quality parameters improves by increasing the number of geophysical profiles utilized.

Another survey of literature investigated the results of several coal quality indices in virtue of the agglomeration characteristics at the coal combustion process. The influence of seven main indices identified was calculated using the entropy method and, in this way, on being combined with the results of the combustion test, the proposal of a broad coal quality index was reached presented by means of mathematical models that enabled the evaluation of the coal agglomeration characteristics, together with the corresponding empirical formula and the discriminant limits [23].

Concerning the qualitative analysis of the spectral properties of coal in the visible region, the reflectance value of the coal analyzed is less than 0.1. However, in the NIR region a marked increase in the pattern of reflectance occurs, which remains until ~1630 nm. Despite small differences between higher and lower ranked coal, all the samples presented characteristics of broad absorption in the visible region. It was then found that "[...] the change in the form of the spectral profile, inclination, intensity of absorption and absorption band reveal the change in the degree of coalification and supply the base for coal classifica-

tion" [20] (p. 5). This study proved efficient since, with its results, it can be found that the spectral responses of coal in the Vis-NIR-SWIR region can be used rapidly and economically in a notation of coal classification, an extremely useful method in thermoelectric plants and mixing operation plants.

Taking a look at coal from a different perspective, Bandyopadhyay and Maiti [24] state that in order to achieve sustainable mining, strategies are needed to evaluate the result of the soil quality recovery. Thus the restoration of degraded lands has become a globally important factor, and it is a factor to minimize the impacts of unsustainable soil management. Responding to this need, the General Asssembly of the United Nations established Agenda 2030, with the 17 Sustainable Development Goals (SDG). The authors also point out that the restoration of soil quality is a process that depends on the age of the reforestation and type of land use after the mining stage. "Generally, pedogenesis in rejects from sterile mining wastes is a complex and lengthy process that involves topographic and geological alterations, and thus the quality of soil improves." (p. 12).

After their research and studies, Bandyopadhyay and Maiti [24] concluded, from the use of two types of selection of indicators and two scoring methods for restored chronosequence environments compared to the forest of reference, that the soil recovers over time. "The results indicated that organic carbon, exchangeable potassium, cation exchange capacity, percentage of sand, microbial biomass carbon, dehydrogenase activity and fluorescein diacetate activity" (p. 1) were configured with the most significant variables in the impact of soil quality. As regards the set of linear minimum score data, this was pointed out as the most adequate because of the higher F correlation coefficients and coefficient of variance values. Finally the RF type is pointed out as the most outstanding to detect soil quality.

Lastly, in terms of coal quality management, the manuscript by Yüksel *et al.* [25] has a personalized EnKF (Ensemble Kalman Filter) approach to update the coal quality properties in real-time, enabling a significant improvement as regards the forecasts, potentiating the increase in coal recovery and process efficiency. The study revealed applicability in a mining environment, which presented a marked improvement in prediction in the model of resources.

5. Final Considerations

The historical relevance of coal is perceived because it has proven to be a decisive element that modified the economic trajectory of those who owned its exploitation. It was also outstanding as the main source of energy in the world and even losing space to oil, it is the main one when electricity is mentioned. It may have been used by the first human beings and was very important in the industrial revolution. Mineral coal presents great advantages compared to other sources of non-renewable energy such as oil and natural gas, for instance, its greater abundance and lower cost; on the other hand, it is also one of the most polluting fuels.

For this, considering the universe of mineral coal and its widespread utilization, especially for electric energy, in its approach the study presented state-of-art considerations regarding coal quality, in the sense of measurement, and the methods utilized for this, considering that the absence of efficient control may generate problems in the supply chain.

In the scientific context, it was concluded that few studies have coal quality as their central topic, both as regards manuscripts of measurement methodology, and also attached to management, because they do not approach the production chain involved, considering the mining company, logistic entity, test laboratories, and power generator, and denoting the lack of a systemic look at the chain.

Therefore, it was perceived in the studies, measurement methodologies, such as Random Forest, which in its logic it functions as a decision tree for classification, and also the PI controller that resets, more precisely, the changes in coal quality, besides the Logistic Regression and Support Vector Machine approach. The search for automation in using some algorithms and mathematical calculations was also perceived. As regards solutions for coal quality management, a study was found that proposes this approach, focusing on real-time updating of the properties of coal, as well as their application and validation.

In this way, considering the need to improve the coal quality process as regards not only verification but also classification, and flexible management of quality control, a future study is proposed of a methodology applied to a computational model aiming to organize the processes and especially the efficiency of communication between the parts involved, bringing to the surface automation mechanisms for the carboniferous production chain.

Conflicts of Interest

The authors declare no conflicts of interest.

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